2011 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
MODELING & SIMULATION, TESTING AND VALIDATION (MSTV) MINI-SYMPOSIUM
AUGUST 9-11 DEARBORN, MICHIGAN

EFFICIENT HYBRID PROPULSION SYSTEM DEVELOPMENT AND VEHICLE INTEGRATION

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ABSTRACT

This paper will incorporate product development methodology from the FED program where AVL is responsible in collaboration with World Technical Services Inc., for delivering a fully developed hybrid propulsion system integrated into the demonstrator vehicle. Specifically, the paper will discuss via case study the unique methodology employed by AVL Powertrain to develop, validate, and integrate our hybrid propulsion system into the FED vehicle. Content will include traditional and virtual powertrain development methodologies that maximize product development efficiency, ensure a robust final design, and minimize development costs. Hybrid controls development, calibration techniques and vehicle design issues will also be discussed.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **10 AUG 2011**	2. REPORT TYPE	3. DATES COVERED
4. TITLE AND SUBTITLE **EFFICIENT HYBRID PROPULSION SYSTEM DEVELOPMENT AND VEHICLE INTEGRATION**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Jeffrey Holtz; Faisal Uppal; Pratap Naick**		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **AVL Powertrain Engineering,Energy Systems Engineering,47519 Halyard Drive,Plymouth,MI,48170**		8. PERFORMING ORGANIZATION REPORT NUMBER **#22041**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**10**	

INTRODUCTION

Today's emphasis on rapid development cycles and utilization on commercial off-the-shelf (COTS) components, to minimize total costs and time to production, has stressed the need for a high amount of upfront design and planning. The boundaries and constraints of the programs technical objectives have pushed the component decision stage further and further forward requiring a deeper knowledge of potential roadblocks and the ability to react quickly with ever-changing difficulties. A thoughtful methodology for execution of development, validation and integration of the hybrid system is critical to achieve a robust and cost effective solution.

This paper is a follow-up of [1]. It will discuss AVL Powertrain Engineering, Inc. (PEI) methodologies used during the control development stages of the Fuel Efficient Ground Vehicle Demonstrator (FED) project to increase the development efficiencies and reduce program timing and costs while maintaining a robust solution.

MODELING AND SIMULATION

Advanced vehicle modeling and simulation is performed in AVL CRUISE [2] software for the prediction of vehicle fuel economy and performance. This also assists in appropriate cost and effective sizing of system components. The vehicle dynamics and standard powertrain components are modeled in AVL CRUISE, whereas the hybrid control algorithm and advanced powertrain components are developed utilizing model based design in MATLAB/SIMULINK and deployed as a standalone dll for use within CRUISE (See section *DLL inclusion to AVL CRUISE*). Some of the most important aspects of this type of modeling/simulation are to strike the right balance between modeling complexity, transparency and accuracy and the ability to utilize real measurements and parameters within the simulation model [3,4,5]. Moreover, it is also important to build a single core control model in order to minimize effort of developing and maintaining separate models for simulation and target hardware. Figure 1 shows an overview of the hybrid system layout with main powertrain components from a system viewpoint.

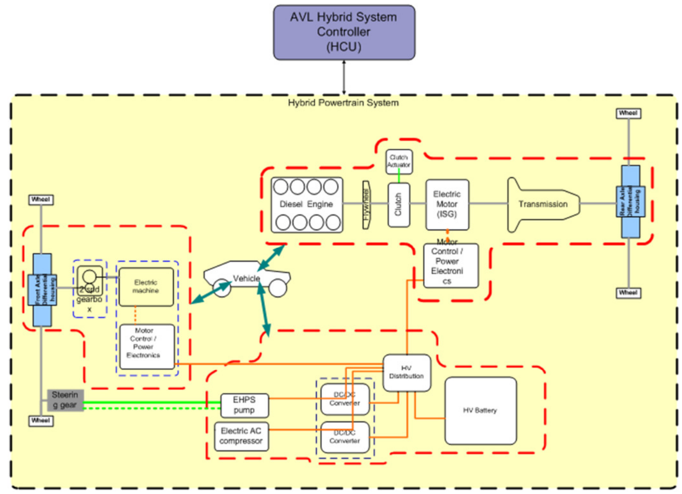

Figure 1 - Hybrid System Layout

This initial vehicle model is then used to develop, test and compare a number of power and energy management strategies. The main goal of the algorithm development is to improve fuel economy by optimizing the overall hybrid system efficiency while maintaining vehicle drivability and performance.

AVL CRUISE Control Design

With the vast number of COTS components that are now available for use for hybrid development vehicles, system architects and control algorithm designers need to be able to maintain flexibility in their model layout.

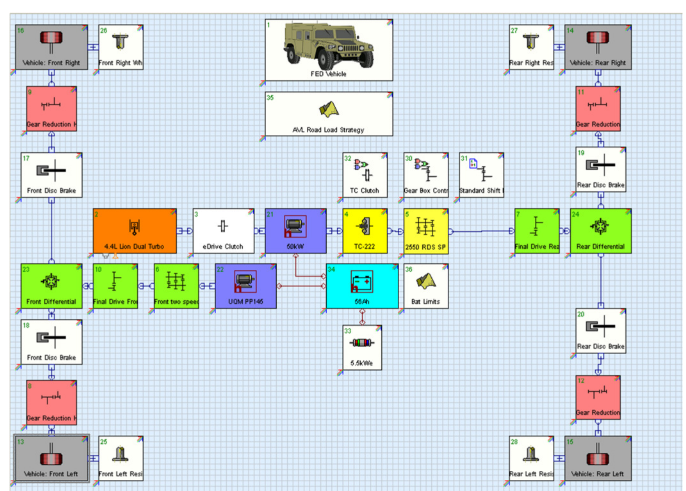

Figure 2 - AVL CRUISE model overview

Figure 2 gives a top level description of the simulation model. There are three propulsion sources in this vehicle: Internal Combustion Engine (ICE) (orange),an Integrated Starter Generator (ISG) (purple) and the front motor

(FMOT) (purple). As mentioned before, a model based approach is used for the control algorithm development.

AVL CRUISE consists of longitudinal vehicle dynamics and all powertrain components. These include: ICE, engine disconnect clutch, ISG, 6-speed automatic transmission, differential, final drives at the rear axle; FMOT, 2-speed manual transmission, differential, final drives at the front axle; and battery, wheel end reduction units (WERU) and wheels connecting the two axles together.

ICE and ISG constitute a parallel hybrid system whereas the inclusion of the FMOT adds Through-The-Road (TTR) hybrid functionality [6]. The main task of the energy management and control design is to utilize all three propulsion sources in the most fuel efficient manner while ensuring minimal performance characteristics.

The controller model developed consists of signal conditioning and powertrain management functions including driver demand calculation, torque management, safety limit monitoring and fault tolerance, component/local and system/global efficiency calculations, power split based on energy management and real-time optimization.

Three main modes of powertrain operation are 1) Engine only, 2) EV only and 3 Hybrid. There is a great emphasis of smooth transitions between these different modes under varying driving conditions.

Rigorous dynamometer testing is performed to characterize and perform initial integration of main hybrid components. The data gathered from the dynamometer testing is used to further fine tune and improve vehicle simulation and control software. Samples of the types of characterization data needed for different powertrain components include; efficiencies, full load curves, thermal characteristics, fuel maps, and shift maps. These key characteristics are confirmed during the dynamometer testing phases and fed back into the base simulation to adjust control parameters and strategy. These modifications can further help steer performance and fuel economy improvements.

DLL inclusion to AVL CRUISE

Through Model-Based-Design (MBD), today's control software has become a living document which provides many different functions along the software development cycle; Requirements Specification, Documentation, and Validation. One prime reason to embrace this controls approach is to achieve cross-platform deployment.

By constructing the core application code utilizing a MBD approach, the container in which the control code is executed can be relocated based upon the desired usage. Figure 3 shows how the same application code can be recompiled using a hardware abstraction layer (HAL) to be used either for target application or inclusion into a software-in-the-loop (SiL) simulation environment for verification and help induce a quicker development cycle.

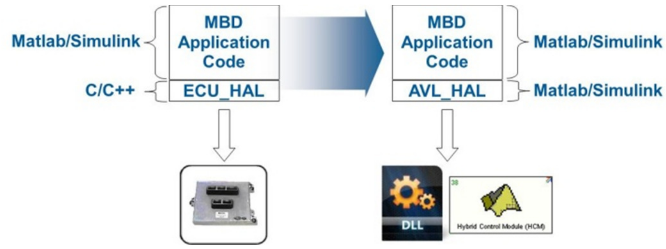

Figure 3 - MBD Application Code Abstraction

Once the application code has been translated into the appropriate format, it can be utilized by different functional developers. For System Level Development, the code can exist as a component inside AVL CRUISE, see Figure 4. For Controls Level Development, the vehicle model can be included as a component inside of the application development environment, see Figure 5. Each functional developer can concentrate on their own unique area of expertise, while both utilizing the others latest development release.

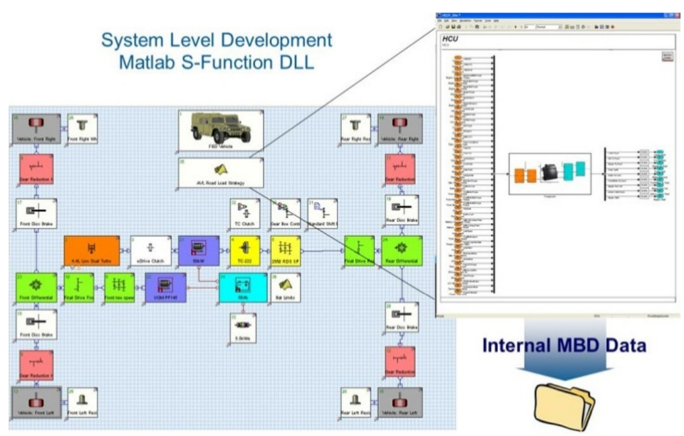

Figure 4 - AVL CRUISE - System Level Development

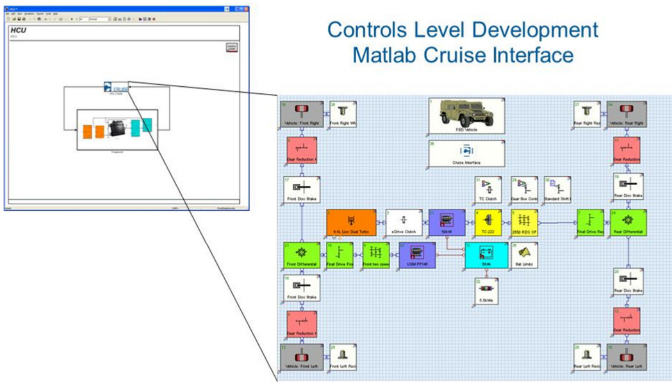

Figure 5 - AVL CRUISE - Controls Level Development

Component Re-evaluation

As described earlier, one of the main objectives of performing simulations is to help in sizing of available COTS components. Individual component selection criteria is based on efficiency, performance and drivability requirements with respect to overall system cost. After architectural concept selection and initial procurement, components once eliminated needed to be re-evaluated when commercial issues arose. One such issue was the transmission selection.

Initially an Automatic Manual Transmission (AMT) was selected for two separate reasons; 1) to reduce driveline efficiencies and 2) to allow pure EV drive mode, since the input shaft could come to a standstill. During procurement, issues arose with the vendor which forced us to re-evaluate the cost benefit tradeoff between the AMT and a standard Automatic Transmission. Rapid modeling changes and initial control development allowed evaluation of alternative solutions and vendors. To overcome the EV drive issue utilizing a torque converter, the ISG must maintain an idle speed control loop to supply the required hydraulic pressure. (See section *Calibration Challenges* for issues arising from this)

Plant Model Reduction

The energy management algorithm calculates component energy availability, driver demanded torque and manages the distribution of power between propulsion components. This includes a real-time optimization function for the power split between the three propulsion sources, namely ICE, ISG and FMOT. This task is found to be potentially computationally intensive and demanding in comparison to other hybrid control functionality. This efficiency based power split uses pre-determined and stored efficiency maps for the ICE, ISG, FMOT, front and rear transmissions and final drives. In order to have the modeled code execute within the embedded target selected, several simplifications are needed including reduction of efficiency map lookup table sizes and adjustment of processor foreground task timing.

For the optimization task, an objective function is constructed that reflects the overall power loss in the main powertrain components. This constitutes a minimization problem that requires evaluation over several iterations. In order to minimize the computational effort, a careful compromise is required between the number of iterations and the minimization goal. In addition, the data types used for all variables in the generated code are cautiously selected. This limits the processing requirements for the hardware target, while maintaining acceptable algorithm accuracy.

The requirements of the algorithm are quite high as real-time optimization is performed. During the initial algorithm development under SiL, the algorithm is allowed to grow in execution time to evaluate the maximum potential fuel savings. In order to realize this algorithm on the hardware target, multiple sample times are employed for different computational tasks to reduce overall processor requirements; e.g. foreground task, interrupt task and background task.

The foreground processing time contained the torque demand calculation, power split and SOC management. After various iterations evaluating driveline control performance this task's loop time was modified from 5ms to 25ms to allow a finer search area within the efficiency space.

The I/O tasks, including Analog Digital Conversion (ADC), and CAN message acquisition are allowed to run at an interrupt level to guarantee reception of key sensor information. A message queue is kept for each of the CAN messages and evaluated in first-in-first-out (FIFO) order when the foreground task is executed.

SOC Management

One of the main functions of energy management component is controlling the high voltage battery state-of-charge (SOC). It aims to maximize vehicle fuel economy while maintaining SOC within safe and acceptable limits. In order to maximize battery life and usable capacity for propulsion and regeneration, it is generally desirable to operate it within tightly controlled bounds around the mid range. However, in order to obtain a long EV range a high initial SOC is required. In determining the compromise

between these two objectives, a number of drive cycles were selected specifically for this vehicle's desired application and used during the simulations for determining this tradeoff.

For a direct comparison between different drive cycles and vehicles, it is essential to have the initial and final SOC as close as possible rather than relying on a fixed SOC penalty factor towards the end of the simulation due to component efficiency losses.

To deal with this, SOC management upper and lower variable bounds are defined within which the battery SOC is maintained. While always allowing maximum possible regeneration, the e-motor propulsion power limit is varied relative to the maximum and minimum allowable SOC bounds.

Figure 6 and Figure 7 show how this management scheme may be performed with examples at two different SOC operating points. At higher battery SOC the demanded e-motor propulsion power is delivered without applying any upper limits, as shown in Figure 6. When the battery SOC becomes low the e-motor provides maximum regeneration but is limited in maximum propulsion power, as can be seen from Figure 7. This allows the battery to absorb all potential energy savings and cap the maximum propulsion to the sum of the absorbed energy.

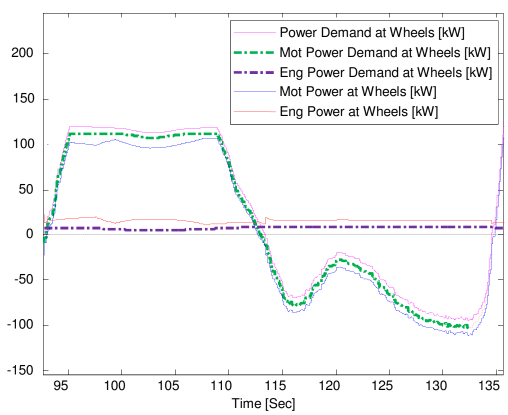

Figure 6 - No eMotor power limits in effect at higher battery SOC

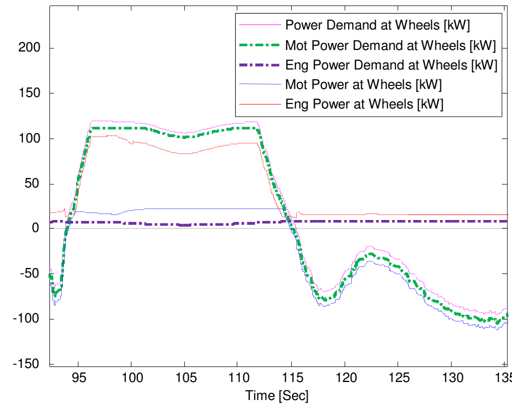

Figure 7 - eMotor power limit in effect at lower battery SOC

Performance/Economy Mode

The trade-off between fuel economy and performance is tightly coupled. The main objective of the FED program is to demonstrate the fuel economy savings potential by utilizing the selected hybrid powertrain architecture. This means that there was little benefit in outperforming the baseline vehicle according to the mission profile. To not exceed the baseline vehicles capability, while also maintaining the potential to exhibit the full performance characteristics of the powertrain, a powertrain mode switch can enable different operating conditions.

While the performance mode allows the vehicle to achieve maximum power by the physical hardware components, the economy mode limits the power at the wheels to the plausible power output of the existing HMMV for the current given inputs based on the current vehicle speed, accel pedal, and brake pedal. From this driver requested power at the wheels, the power needed by the hybrid power pack is translated from the wheels through the driveline components, taking the physical components current efficiencies into consideration.

POWERTRAIN DYNO INTEGRATION

AVL proposes the incremental testing of the powertrain in an advanced powertrain test cell. Each of these tests is targeted at isolating and characterizing the performance and efficiency of the powertrain at a sub-system control level. This division of tasks allows for progressive integration of each of the sub-system controls up through the full

powertrain assembly. This methodology provides a robust means of anticipating and reacting to issues that will be encountered during the demonstrator vehicle testing.

Component Validation

Individual component testing and validation inside the dynamometer is divided into three separate stages of characterization; Conventional Powertrain Testing, Electrical Powertrain Testing, and Hybrid Powertrain Testing.

During the conventional phase, the engine, torque converter, and transmission are tested in isolation. This allows a variety of component specific tasks to occur without the burden or influence from the hybrid components; mapping of base conventional powertrain efficiencies, baseline fuel economy evaluation, sub-system interaction, component validation, and transmission shift strategy. These characteristics are then used as input for the full powertrain efficiency trade off.

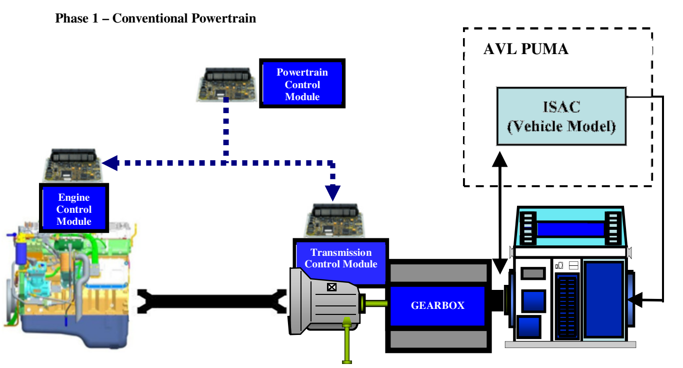

Figure 8 - Dynamometer Phase 1 - Conventional Powertrain

During the Electrical Testing phase, the engine is decoupled from the rear of the powertrain. The ISG is tested for efficiencies across both the generator and motor regions within the engines speed envelope.

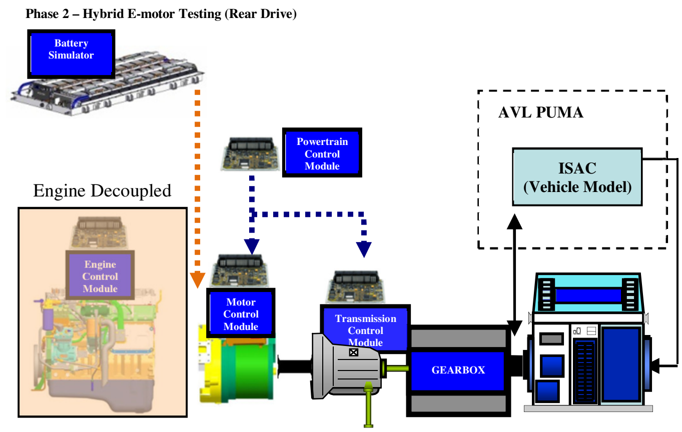

Figure 9 - Dynamometer Phase 2 - Electrical Powertrain

The third testing phase involves integrating the conventional powertrain components with the hybrid components. At this stage, full powertrain split and overall system interactions can be evaluated, this includes: drive cycle simulation, transient response, driveline mode switch, verification of component protection and torque limiting.

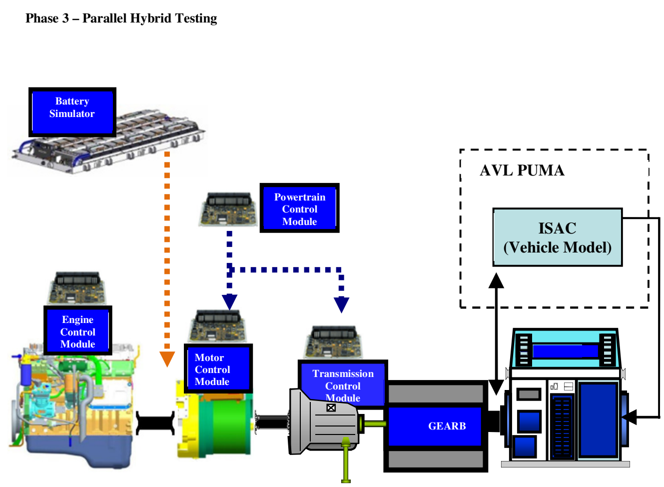

Figure 10 - Dynamometer Phase 3 - Hybrid Powertrain

Component Interaction

The Hybrid Control Unit (HCU) is the top or supervisory level vehicle controller that interacts in a closed loop with the subsystem or component level controllers like the Engine Control Unit (ECU), Transmission Control Unit (TCU), Brake Control Module (BCM), eMotor Inverter Drive Unit (IDU) and Battery Management System (BMS). Figure 11

depicts the top level communication between the HCU and subsystem controllers via three dedicated CAN ports.

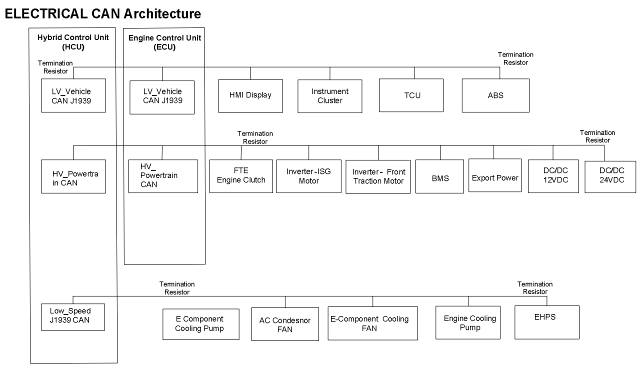

Figure 11 - CAN Topology

HCU computes the power required at the wheels based on driver demands of accelerator, brake pedal and gear status and current driving conditions like road speed and estimated road grade. A power split strategy is set in place that optimally computes the demanded torque for the three propulsion sources based on a pre-defined objective function that takes powertrain energy losses into account.

The HCU demands the required torque from ECU, ISG, and FMOT via CAN messaging, similar to the torque structure defined in J1939 standards [7]. The HCU acts as the main propulsion controller to the transmission by monitoring and interacting via J1939 messaging structure, controlling the disconnect clutch between engine and ISG, and estimating accessory load power requirement for the vehicle and other equipment.

An important drivability and component durability aspect, as mentioned before, is smooth transitions between the powertrain modes (Engine Only, EV Only and Hybrid). HCU also has the responsibility to switch between these modes in a way that result in minimal driveline harshness on the powertrain and other system components.

ECU I/O Pins

One limitation on the implementation of the specified system architecture is the number of Input and Output (I/O) pins available on the chosen processor as the Hybrid Control Unit (HCU). The required I/O for the vehicle is split between the ECU and the HCU. Examples of this include the acceleration pedal position (APP) and brake pedal position.

The ECU receives the analog inputs of both pedal positions and executes all necessary fault handing checks. This helps reduce load on the HCU and allows a fallback conventional implementation of the powertrain during hybrid component unavailability. During nominal operation, the ECU transmits these inputs over the CAN network in standard J1939 protocol Suspect Parameter Numbers (SPN) [7]. After reception by the HCU, the efficiency power split algorithm re-interprets the necessary throttle position of the engine and utilizes torque/speed control (TSC) messaging to implement its constraints on the ECU.

Virtual Component Development

The concept selection of a TTR hybrid architecture provides new challenges when trying to plan for testing within the dynamometer validation and initial controls development phases. The multiple power sources means that an advanced, multiple dynamometer, test cell is needed. Another option is to delay the full architecture development until the vehicle integration phase. The final solution is to develop a virtual component implementation. This removes the need to expand testing into advanced dynamometer facilities thereby reducing program costs and reducing the time needed for powertrain integration into the vehicle. The front axle of the powertrain can exist as a simulated component and its contribution to the overall vehicles propulsion can be added to the virtual vehicles model input.

The control interface to the front axle components consists of CAN communication which are received by the dynamometer controller, AVL PUMA, and passed to a real-time model to compute load and thermal demands. Likewise the battery system is replaced with a power cycler, AeroVironment ABC150, with control through the battery testing automation platform AVL Lynx. A battery model is implemented in real-time to combine the actual power draw from the physical ISG in the test cell with the virtual components being modeled. Thus the full development of the HCU as a powertrain controller could then continue as if all components are available.

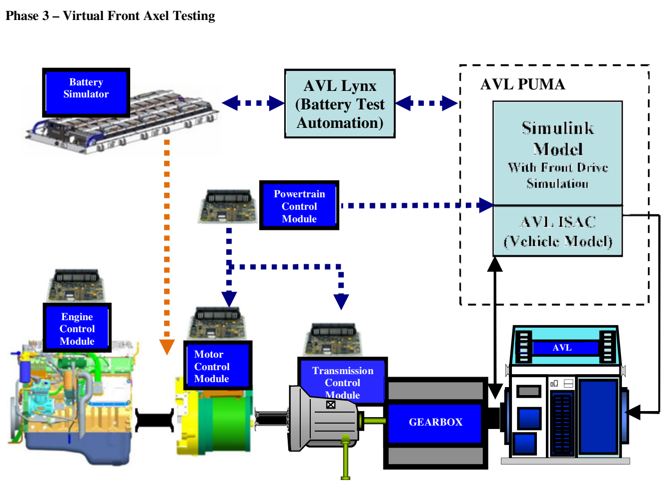

Figure 12 - Virtual Axel Topology

Implementation of the virtual front axle powertrain is accomplished by translating the power source of the front motor through the front gear box, WERU, to the road, and then back through the rear wheels. The resultant torque on the dynamometer by the rear powertrain is then summed with the front axle's contribution and fed into the vehicle model, AVL ISAC, to complete the full powertrain simulation.

Serial Brake Development

During early component sizing and architecture layout the decision was made to forgo a hybrid brake blending solution due to the complexity and cost. Instead a serial brake blending approach is used, utilizing a standoff gap between brake pedal travel and hydraulic brake engagement.

The first 34% of brake travel is set as a deadband area to the hydraulic brakes. This area is dedicated for complete hybrid regeneration, no foundation brakes are engaged. From this pedal travel forward, both powertrain regeneration and foundation brake are used. This allows the first portion of braking to capture the maximum amount of electrical energy and reduce the overall fuel economy.

Since the braking power at the wheels delivered by the foundation brakes is proportional to the speed in which the vehicle is traveling, the method for phasing in the regenerative braking needs to accommodate the change in total braking power. The goal should be to achieve as close to a linear braking power engagement, relative to the brake pedal travel, as possible.

If a straight linear ratio is used, where by the regenerative power is proportional to the brake pedal, referenced to the maximum total power, a plateau appears in the middle of the brake pedal travel during higher speeds. In this case the total power is below the desired linear curve, see Figure 13. Likewise, a braking bump, where the total power is above the desired linear curve, can also appear during slower speed, see Figure 14.

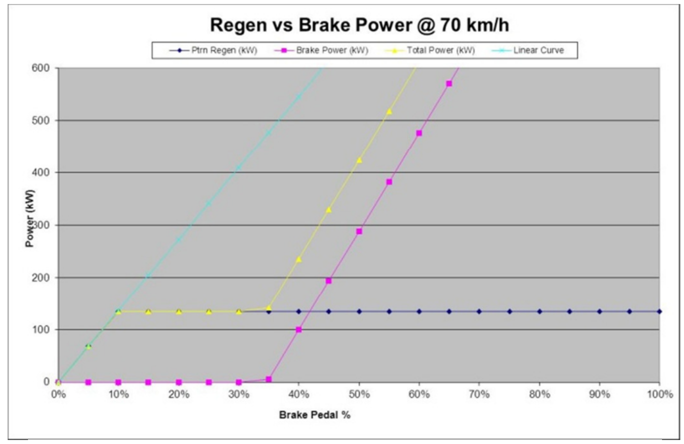

Figure 13 – Linear Regeneration during High Speeds

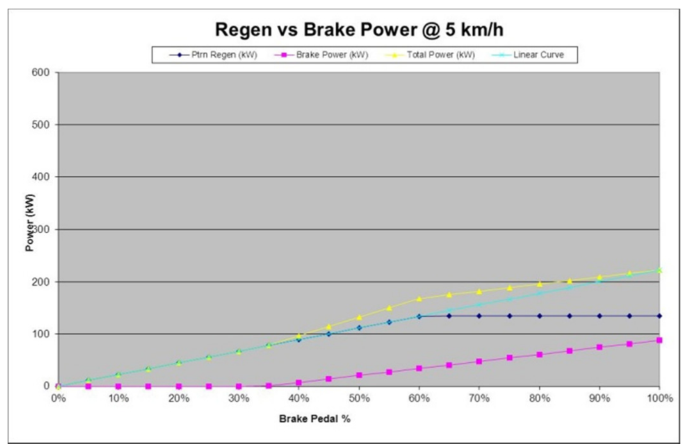

Figure 14 – Linear Regeneration during Low Speeds

An adaptive blend of the powertrain regeneration is needed and is implemented. Up till the end of the deadband area, the regenerative power is ratio metric to the maximum total power. Once the foundation brakes are applied, the regenerative brakes will perform a fill between the desired linear line to maximum total power and the foundation brakes, note differences between Figure 14 and Figure 16.

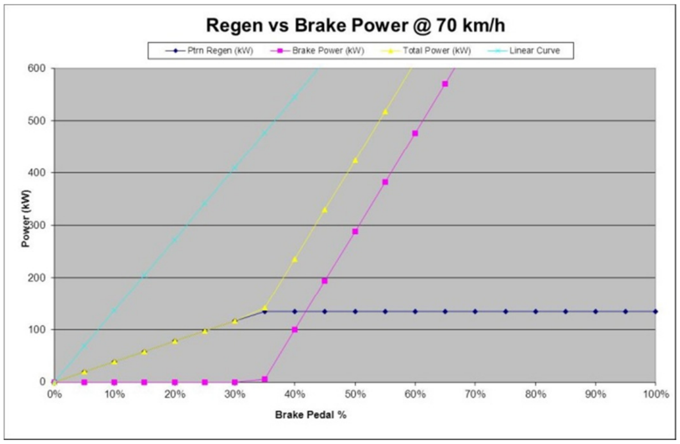

Figure 15 - Adaptive Regeneration at High Speeds

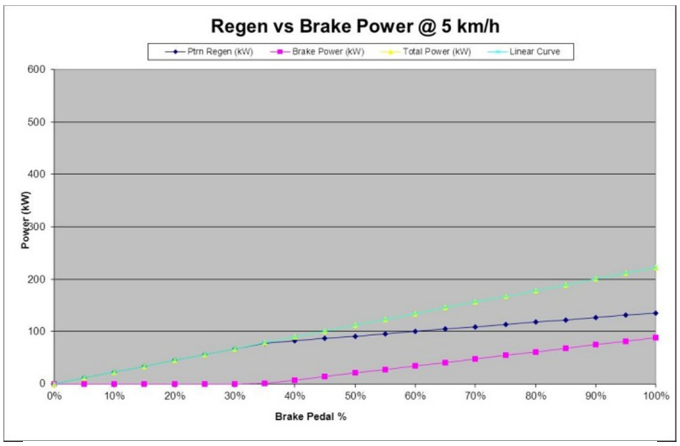

Figure 16 - Adaptive Regeneration at Low Speeds

Calibration Challenges

Due to the virtual components during dynamometer development and testing, the interaction between the front and rear axles of the powertrain could not be fully tested and will be performed on the vehicle during powertrain integration. Similar to the way the components in SiL testing need to be updated in AVL CRUISE after dynamometer testing, vehicle simulation parameters used in the test bed automation system can differ from the final vehicle configuration.

Another calibration challenge is the tuning of the two idle speed control strategies utilized in different powertrain modes; ECU idle speed control and ISG idle speed control. For example, in the case when the vehicle is slowing down and the engine/ISG reaches the idle speed, a smooth transition from regeneration to nominal idle condition is required to not stall the engine and for drivability considerations.

A major issue when dealing with COTS components, as was the case with the transmission, is the potential for lack of calibration support or calibration availability. The transmission selected was only available with standard shift map selections. Because the HCU acts as the sole power controller to the transmission, this limitation is overcome by manipulating the core input parameters (throttle position and engine load) to the transmission.

VEHICLE DESIGN

During the concept selection phase multiple aspects of the overall design of the vehicle were considered to help with the main objective of reducing fuel economy. The potential improvements from the vehicles standpoint focused on two main areas; structural and thermal. The following sections detail some of the changes that were considered and implemented.

Structural Considerations

Vehicle weight savings is considered to be the major source of improvement in optimizing for fuel economy. Within budget, packaging and functionality limitations, lightweight materials are evaluated and used whenever possible. Some areas that make the biggest difference in the overall weight of the vehicle are in the use of armor as structure. Light weight carbon fiber composites utilized for the front and rear clips and a tubular structural frame, are examples of modifications where a lighter weight alternative were identified and used. The size and shape of the vehicle, sub-systems and components are also minimized whenever possible. This in turn helps to reduce the overall weight of the vehicle and supply improved aerodynamics. These improvements are further used to refine the modeling and simulation results.

Ride Height adjustment is another area of improvement over the base vehicle. This allows the vehicle to meet drivability and handling requirements at lower speed while also improving aerodynamic drag coefficient at higher speeds, thereby improving fuel economy.

Lower rolling resistance tires are also utilized to meet drivability and traction requirements.

Thermal Considerations

The front radiator pack is partitioned into three separate packs to reduce fan load and improve cooling efficiencies. The air conditioner (A/C) condenser and the electronics cooling radiator are packaged in the rear of the vehicle with

separate ducts carrying air to them. This reduces the front fan electrical load from 15kW to 3.2kW, minimizing the overall power draw on the system and allowing for more energy to be available for propulsion.

A computational fluid dynamics (CFD) analysis is performed over the vehicle and the thermal systems to improve air flow and to reduce aerodynamic drag.

CONCLUSION

Development of today's hybrid Ground Vehicle Systems requires coordination between multiple disciplines and a methodical coordinated effort to pull together the multitude of individualized components to form a unique complete solution. Without the free flow of information from modeling and simulation stages into multiple stepped powertrain dynamometer stages and back, the costs and amount of time required to implement a hybrid vehicle can quickly spiral beyond the original budgets.

During the onset of the project, algorithmic control development alongside of system architecture decisions can lead to quicker solutions when potential problems arise from nontechnical influences. This methodology allowed a rapid change in initial concept selection without impact to the final deliverable date.

The dynamometer phase of vehicle development is critical in the designing of complex powertrains. A multiple stepped powertrain phase development allows collection of data on a componentized level. The data is used to refine the initial model and helps in providing early validation of the final design before the final stages of dynamometer or vehicle build. Utilization of virtual dynamometer phases allows the ability to reduce hardware costs and speeds integration efforts later in the development cycle. This approach also removes the developmental constraints on controls by replacing the physical components.

Vehicle design improvements, although cannot be validated till vehicle integration, do have significant influence on the powertrain fuel economy. Their contributions need to not only be explored during the initial modeling phases but also constantly updated during the dynamometer phase to minimize any unanticipated influences on overall fuel economy.

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